EID of a Pilot Support System for Airborne Separation Assurance

Stijn B.J. Van Dam

An L.M. Abeloos

Max Mulder

René M.M. van Paassen

EID OF A PILOT SUPPORT SYSTEM FOR AIRBORNE SEPARATION ASSURANCE

Stijn B.J. Van Dam, **An L.M. Abeloos**, **Max Mulder** and **René (M. M.) van Paassen**

Delft University of Technology, Faculty of Aerospace Engineering, Control and Simulation Division
Delft, The Netherlands

In a flexible airspace environment the pilot disposes of an increased amount of travel opportunities. At the same time the airspace traffic situation becomes more complex and the aircraft separation assurance task is shifted towards the cockpit. The design paradigm of Ecological Interface Design is applied to support the pilot with the airborne planning of efficient trajectory paths that maintain spatial separation from other traffic. The desired pilot behavior is achieved by visualizing travel-relevant airspace affordances in terms of realistic aircraft locomotion. As a result, a novel interface the "state vector envelope" presents safe and efficient travel opportunities in a state vector field. The concept has been evaluated through on-line simulations of a number of basic conflict situations.

Introduction

In traditional airspace environment, capacity problems are expected in the near future due to growing air traffic, hereby causing a higher workload for Air Traffic Controllers. New concepts for Air Traffic Management such as Free Flight permit a flexible use of airspace with airborne determination of User-Preferred Trajectories or UPT's (ACM, 2002) which allow direct routing and cruise climb tasks. This flexible use is expected to increase airspace capacity and improve congestion problems.
The separation task is shifted from the air traffic controller towards the pilot and it is expected that the latter needs to be assisted in this task. The question is whether current systems always fully exploit numerous travel opportunities offered by a more flexible and complex airspace. This extended pilot navigation task of trajectory planning, including separation, needs to be supported by a more general airborne trajectory planning system.

New technologies have already made it possible to assure spatial separation from other aircraft in the cockpit with the so called Airborne Separation Assurance Systems ACM, 2002. These systems predict when spatial separation is going to be lost (conflict detection), communicate this event to the pilot and provide and suggest resolutions (conflict resolution).

ASAS systems, as for example developed by the Dutch Aerospace Laboratory NLR (Hoekstra, 2001) have proved to offer the pilot a safe and effective conflict detection and resolution with speed and heading markers. Unfortunately, the system can not prevent that the aircraft resolution maneuver resolves one conflict, but triggers another. In the same way, it can not prevent the occurrence of very dangerous short term conflict situations due to trajectory changes like leveling off or turning.

A further development of the NLR system, the Predictive ASAS system or P-ASAS informs the pilot about which state changes would trigger new conflicts by the use of individual no-go state bands on the speed taper and heading scale. Each no-go zone holds for maneuvers in that state dimension. Therefore its use to prevent short term conflict situations is only applicable to aircraft maneuvers that consist of a sole heading or speed change.

Further improvements on these systems should be possible. However, in our opinion there must be a better way to support airborne trajectory planning. The P-ASAS system calculates and presents an explicit automatic solution, which disables the pilot from integrating other trajectory planning- relevant tasks with the spatial separation task. Previous research at the Delft University of Technology (Hoekstra, 2001 & van Paassen, 1999) does not aim to calculate and present an explicit automated solution, but starts from the exploration and presentation of conflict-free trajectory possibilities. Such a presentation helps the pilot to both resolve and prevent conflict situations while the freedom to consider other travel-relevant aspects into the trajectory planning task is preserved.

Besides the fact that it does not support efficient conflict resolution, the guidance tools related to the former locomotion models with instant heading change or turn maneuvers show a high sensitivity to flight speed changes. The no-go zones split up, enlarge or shrink, move from one side to another. Therefore, the research presented in this paper explores the potential of a locomotion model that incorporates the ground speed change to present efficient conflict-free trajectory travel guidance. The aircraft dynamics will be neglected due to the complexity of expressing combined heading and speed changes.

This project took a cognitive engineering approach. As mentioned before, spatial separation is not the only pilot task that needs to be performed for efficient and safe airspace travel. A workspace analysis of the airborne trajectory planning task defines a complete overview of the pilot's work domain. It reveals hierarchic relations between travel physics, planning tasks and the achievement of travel goals in terms of safety, production and efficiency. These relations are made directly visible for ecological interface design by applying a functional modeling technique based on the perception of environmental affordances (Gibson, 1979). At this stage the locomotion model is studied within the conflict geometry and dynamics. As a result a more functional or meaningful, rather than pure physical presentation of aircraft and airspace physics helps the pilot to see the travel opportunities with respect to his planning task. The interface is evaluated through an experiment with on-line simulations of a number of basic conflict situations. Conclusions and recommendations regarding the ecological interface design are given at the end of the paper.

ATP Work Domain

In a flexible use airspace environment the extended navigation task, which includes spatial separation, will be defined as airborne trajectory planning task.

Airborne Trajectory Planning (ATP) is a general concept addressing the on-board planning of a travel goal satisfying trajectory path within a flexible use airspace environment

By setting up an abstraction hierarchy table (Figure 1) for this task, travel goals, on functional purpose level, are related to the abstract key functions and to physical models of airspace and aircraft. This way a multi-level overview of the pilot's work domain is obtained. The key functions will be used to set out the planning task description.

The ATP systems' main goal is traveling through airspace. Three sub-goals are identified on a functional purpose level: safety, production and efficiency. On a abstract functional level the key functions reveal how the goals can be achieved. On the general functional level traveling and path control have to realize these key functions. On the bottom of the table the aircraft and airspace model represent the physical form of the system. For trajectory planning, the workspace is reduced to short- and middle term locomotion issues in the horizontal plane.

General air transportation key functions such as staying inside the flight envelope, assuring propulsion and lift, providing passenger comfort are not relevant for the locomotive trajectory path. Although trajectory planning is done in a 3D airspace environment, vertical maneuvers are excluded in order to focus on the horizontal space domain. In the horizontal plane an aircraft will travel towards a chosen waypoint or destination. As the planning task is applied to multiple conflict situations, the look-ahead time for conflict support ranges from short to middle term.

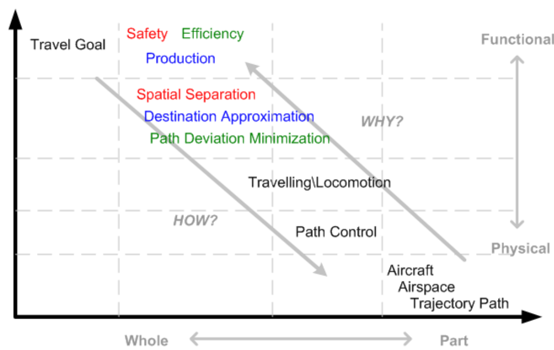

Figure 1. *Abstraction Hierarchy for Airborne Trajectory Planning system.*

Now that the domain boundaries are clearly outlined, the identified Key Functions involved are spatial separation, path deviation minimization and destination approximation. These key functions are evaluated against measurable physical criteria. These criteria are deduced from physical properties of aircraft and airspace and the relation between these properties.

Spatial Separation (safety goal). The violation space around an aircraft is defined in the separation criteria ACM, 2002. The point on the trajectory prediction, which lies within the 5 minute look-ahead time and where the spatial separation with the other aircraft is smaller than the minimal value, is called the Closest Point of Approach (CPA). In the horizontal plane the CPA distance has to be larger than 5 nautical miles.

Destination Approximation (production goal). A destination can be the destination of a flight, but also the next waypoint or the next entry or exit point on the border of another airspace. Often, spatiotemporal requirements need to be met for arriving at that point: a maximal spatial and time deviation. For this study, a simple requirement stating that the distance between aircraft and destination should always decrease in time (therefore called destination approximation), will be used.

Path Deviation Minimization (efficiency goal). The path deviation is parameterized by the maximal spatial deviation. This distance is the 3D distance between the original and alternative trajectory position point at a given time instance. After passing the closest Point of Approach, the traveler starts its recovery maneuver towards the original trajectory. At this point the deviation distance is a measure for the conflict resolution efficiency.

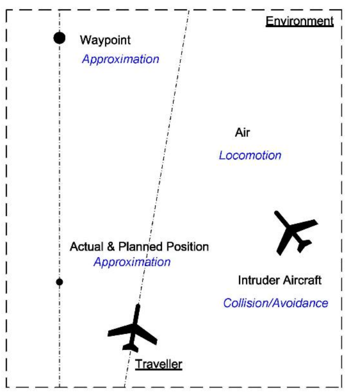

Figure 2. *Travel Space Modeling by the notion of affordances. Airspace elements afford trajectory planning relevant properties.*

Functional Modeling Based on the Perception of Affordances

The step of translating cognitive work analysis of a complex work domain into an interface design is based on a ecological interface design concept developed by Vicente & Rasmussen (Vicente and Rasmussen, 1992). Functional Modeling tries to formulate the behavior of a system relevant to achieving its ends (Lind, 1990). A paradigm of ecological psychology, the perception of affordances (Gibson, 1979), describes the human capacity to directly perceive and act upon environmental affordances, rather than the assessment of physical qualities or properties. For trajectory planning, the goal relevant affordances must be formulated or visualized in such a way that the perception of these by the pilot, directly triggers desired goal relevant or functional aircraft behavior by the pilot's steering actions. Figure 2 provides a pictorial overview. The surrounding unoccupied air provides the affordance of locomotion to the aircraft, other aircraft in the vicinity provide the affordance of collision (or the opposite, avoidance). Note that currently the listed affordances are not yet visualized adequately.

Locomotion Model

In order to assure that the perception of affordances can be fluently transformed in functional aircraft behavior, the affordances are formulated in terms of aircraft locomotion that matches flight practice. For trajectory planning in a cruise flight limited to the horizontal plane, the pilot determines its aircraft behavior by manipulation of heading and airspeed settings, while the autopilot flies on altitude hold mode. Therefore, a locomotion model should yield heading and/or speed change. In this way the model, reduced to a one or two dimensional input, is less complex and more practical than a traditional multidimensional state space presentation. As explained in the introduction, the two first locomotion models explore travel opportunities through heading changes, either instantaneous or including realistic turn dynamics. Because of their lack of conflict resolution efficiency and their sensitivity to speed changes, a third model is built which combines speed and heading changes.

Visualization of Affordances

For productive planning, the affordance of approach to or deviation from the waypoint is simply visualized by drawing the waypoint on the navigation display. The pilot will realize functional behavior through turn maneuvers that turn the waypoint symbol right in front of the aircraft symbol. A locomotion model that enables heading changes is compatible with this visualization. For safety however, the simple presentation of intruder aircraft symbols on the navigation display only gives the pilot a mere notion of crashing and avoidance, not a meaningful perception. The visualization does not reveal which aircraft behavior avoids the intruder. Insight into how the motion of the own aircraft (locomotion) and the intruder realize the spatial separation, is obtained by considering the motions of the vehicles in a relative velocity plane that describes the own aircrafts motion relative to the considered intruder aircraft. The heading travel function, the locomotion model based on real turn dynamics (De Neef, 2002), calculates which turn maneuvers will cause a loss of separation in this plane and shows these turn maneuvers on the heading scale of the navigation display. The weakness of the guidance offered by the heading bands alone lies in the perception of efficiency goal related affordances. An off-line simulation proved that in a conflict situation, a resolution maneuver towards the closest heading band edge could lead to a larger lateral deviation from the original trajectory than a resolution maneuver to the other band edge that was situated further away. The perception of the angular proximity of the heading band edge and steering towards it, does not yield aircraft behavior that results in a minimal trajectory deviation.

In the relative speed plane, the relative velocity of the subject aircraft is described with respect to the considered intruder. A beam shaped area can be defined, outlined in Figure 3, by two lines originating from the own position and tangent to respectively the left and right side of the Protected Zone (PZ) of the intruder, at its present location. This zone is called the Forbidden Beam Zone (FBZ) and in Figure 3 the triangle indicates this zone. If the relative velocity vector is inside this area, the trajectory path will eventually enter the PZ and spatial separation will be lost.

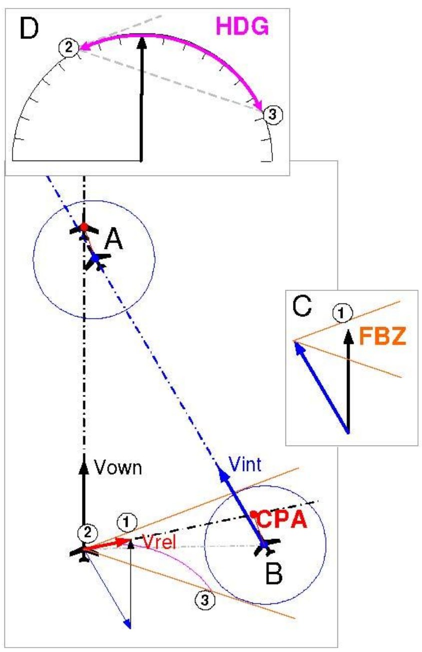

Figure 3. *Conflict Presentation in the absolute (A) and relative (B) velocity plane. Box (C) shows how the FBZ cuts out vector states. Index 1 shows a possible resolution state. Box (D) shows the heading band principle. Index 2 and 3 show the needed turn maneuvers. Vrel is the relative velocity with respect to the intruder aircraft. The circle around the intruder aircraft symbol is the Protected Zone (PZ)*

Separation can be realized by actions that will cause the relative velocity vector to lie outside the FBZ. As the relative vector is constructed by the own vector and the intruder vector, spatial separation can be realized by a vector state change (= aircraft maneuver) of the own vector, the intruder vector or a combination of those. Note that the magnitude of the relative speed vector is inversely proportional to the amount of time it takes until actual crashing or avoiding will take place. The origin point of the FBZ represents the point where relative velocity is zero. This means that when both aircraft have the same vector magnitude and heading, their relative position does not change in time. The Vector Envelope Map in Figure 3 shows all vector state possibilities that would assure separation.

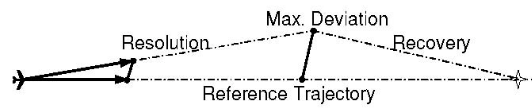

Figure 4. *Maximum deviation distance depends on the magnitude of the state change and the duration of the conflict resolution.*

The aircraft symbol at point "A" in Figure 3 shows the projected future location of the intruder aircraft at the closest point of approach. A visualization of this point does not lead to a useful display, since it will move considerably as avoidance maneuvers are performed; conflicts between aircraft have to be solved with heading and speed changes, and a presentation in absolute geometric space in this case does not provide the proper information to do this.

$$Deviation[m] = \left|V_{res} - V_{ref}\right| * t_{res} \qquad (1)$$

Another issue to be considered is the efficiency of the chosen solution. Path deviation is quantified by the maximal spatial deviation (Figure 4). This is the distance between the actual and planned position of the own aircraft at the CPA instance. At that point the pilot will start the recovery maneuver in order to fly the aircraft back towards the original trajectory. The deviation due to conflict resolution is determined by two physical phenomena: the state change magnitude and the duration of the resolution or simply resolution time.

$$Deviation[m] = \left|V_{res} - V_{ref}\right| / \left|V_{res} - FBZ_{orig}\right| \qquad (2)$$

Consider again Figure 3. The relative speed vector is constructed by taking the opposite of the intruder speed vector, and adding the speed vector of the own aircraft. In this graphical representation the end point of the relative speed is always lies at the end point of the absolute speed vector. Multiple conflicts can be combined in a single solution space by co-locating the end-points of the relative velocity vectors, as done in Figure5.

In the bottom part of Figure 5 one can see that the vector map presentation as it will be presented on the navigation display. The half-circles represent the maximum and minimum velocity boundary in which the pilot is allowed to operate. Also the heading change is limited to 90 degrees port and starboard in order to show travel opportunities that will yield destination approximation.

An aircraft maneuver of an intruder will be perceived by motion of the related FBZ. The pilot can directly act upon this motion if necessary. By steering in the opposite direction, a cooperative maneuver is realized with the perceived intruder maneuver. In a one-to-one conflict, the geometry of the envelope from the point of view of one aircraft is complementary to the other one. In Figure 6 one can see that moving against the direction of the other aircraft will cause the pilot to end up at the opposite FBZ leg. Furthermore, the closer one aircraft lies to one leg, the closer the other aircraft will lie to the opposite leg. Physically this means for example that, if one aircraft is close to the border that makes it pass the other at the left upper side, the other aircraft will be closer to the border line that will make it pass the first aircraft at the right lower side. In this way, cooperative maneuvers will always be initiated, even if both aircraft would begin their maneuver exactly at the same time.

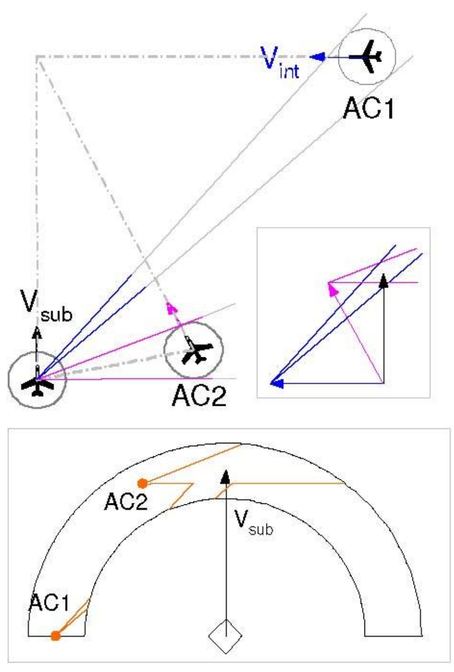

Figure 5. *Combination of the Forbidden Beam Zones for different conflicts, plotted in a vector map with the allowable heading and speed range, into a vector map showing heading and speed affordances.*

During the time that the own aircraft is approaching the intruder aircraft, the subject aircraft will get closer to the PZ and therefore the FBZ-beam will expand in time. The envelope presentation is based on direct state changes, so the geometrical form of the solution space does not take into account the beam expansion that evolves during the time period that the state change is realized. In Figure 7 a starboard turn maneuver is started by the subject aircraft at t(0) and is ended at time t(1). The solution state on the FBZ edge at the beginning of the maneuver will still lie inside the FBZ at time t(1),as the beam expanded during the time interval. The closer to the CPA instance, the more significant this phenomenon will become.

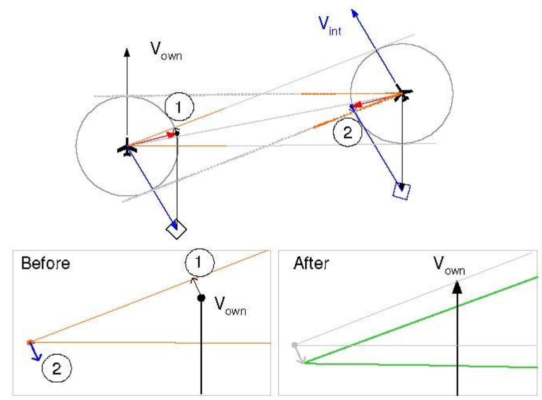

Figure 6. *Cooperative maneuvers of subject aircraft (1) and intruder aircraft (2).*

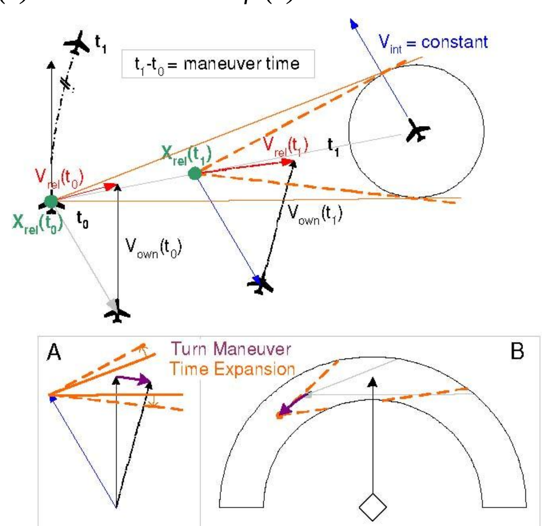

Figure 7. *Illustration of the time expansion of the FBZ during a resolution maneuver.*

Experiment

The state vector envelope principle was evaluated in a small a pilot experiment in a fixed-base flight simulator. Six pilots, aged 27 to 38, participated in the experiment, with experience ranged from a few hundred to three thousand flight hours. The pilots were asked to fly an IFR track between two waypoints in cruise flight conditions on an altitude of 30000 ft. At a given moment a conflict situation was detected and the pilot was asked to make a maneuver (using autopilot settings) that would result in a safe and efficient conflict resolution. When the intruder aircraft had passed by, the pilot began a recovery maneuver by going back to the original cruise speed and heading towards the next waypoint in order to continue its cruise flight on the original trajectory. They were instructed about the functioning of the speed vector envelope, and that the origin points of the other aircraft will yield a parallel trajectory at the same airspeed with the related intruder aircraft. During resolution the subject was allowed to change its strategy and to cross the forbidden zone to realize this change, as long as spatial separation with the intruder aircraft was maintained. Five different conflict geometries were simulated. No reference or other display designs were used, as the limited set up of this experiment investigates the feasibility of the newly designed guidance tool. First the pilots were briefed about the interface concept and the experiment design. Then 2 training runs and 5 experiment runs were done in the simulator. The training scenarios were similar but not equal to the experiment scenarios. Each run lasted 8 to 10 minutes. After the whole set of runs, the pilot was asked to fill in an evaluation form. The aircraft model used in the simulation was a Boeing 747-200. The aircraft was flying a cruise flight at 30000ft. Initial Velocity was chosen 0.8 Mach, about 240 m/s ground speed. The autopilot was enabled and IAS and heading could be manipulated on a virtual Mode Control Panel. The conflict algorithm for the subject aircraft, detects for the actual speed a future spatial separation violation of the 5 nm standard within 5 minutes look-ahead time. At his moment the envelope lines will be drawn on the display. Each intruder is simulated with a propagation model that defines an initial trajectory by its position, ground speed and heading. At a given time instance a resolution maneuver with a different ground speed and heading is triggered. When the intruders pass each other they will head back to their original trajectory path. The resolutions are human-like and will cause a spatial separation between 5 and 10 nm. The maneuver dynamics consists of simple turn geometry and a constant longitudinal acceleration. Both intruder aircraft only resolve the conflict situation with each other. In other words, they neglect the conflict situation with the subject aircraft. As a result it is possible that the intruder makes a counter-active or hostile maneuver. The occurrence of such an event makes it possible to check for robustness of the interface concept. In 26 out of 30 trials, the pilot's strategies were consistent with the rules for efficient solution of the conflict. In four trials an inefficient solution was chosen, solving the conflict but resulting in a large off-track distance. The behavior of the conflict aircraft was programmed with a pre-defined logic, however, resulting in a two runs with a loss of separation, due to “hostile” maneuvers of the conflict aircraft. Work is underway to provide the intruder aircraft with the proper behavior. All subjects indicated that the envelope interface was useful to them, but indicated that more training would be needed for an optimal comprehension of it. Their points of critique were on the actual implementation of the display (with lines instead of filled or shaded areas), and on the difficulty of correlating aircraft shown on the display with the shapes in the envelope. Another problem was to perceive the time left in a conflict. This was related to the FBZ expansion mentioned above, far from the conflict expansion is hardly noticeable, but closer by (when waiting too long with a solution) expansion would be rapid and prevent a reasonable solution. Two of the pilots quickly gained insight in the display, enabling them to predict and reason about the solutions well in advance.

Conclusions & Recommendations

The state vector envelope interface design is a guidance tool in the horizontal plane for the airborne planning of trajectory paths that maintain spatial separation with other aircraft, approach the destination and limit path deviation while resolving a conflict situation. A locomotion model based on instantaneous combined speed and heading changes describes aircraft motion in a way that it matches flight practice. The realization of the trajectory planning task is based on the pilot perception of travel-relevant airspace affordances like crashing, avoiding, approaching and deviation in terms of combined heading and speed changes. The state vector envelope presentation especially visualizes the affordance of collision & avoidance by the envelope lines and the affordance of path deviation minimization by the envelope origin points. A simple and effective rule and skill based conflict resolution strategy consists of steering out of the forbidden vector zone while avoiding the state vectors of other aircraft. A simple experiment with two intruder aircraft showed that in most occasions the pilot conflict resolution behavior matches with the expected resolution strategy. The pilot feedback underlined that the envelope concept is useful, but more study and training is needed to get more insight in the conflict geometry presented. Furthermore it was difficult to perceive intruder maneuvers and to correlate an intruder aircraft with its respective part in the envelope form. The most important shortcomings however, are the lack of urgency awareness and the expansion of the beam width. It is difficult to predict when the subject aircraft will pass or crash into an intruder aircraft. Combined with the expansion phenomenon, this means that the pilot does not know how much time is left to resolve a conflict, neither how much the envelope edges will expand during the resolution maneuver. The use of different ”urgency layers” for the envelope form and the presentation of the ”time to impact/avoid” give a notion for urgency. The beam expansion could be faced by plotting a future prediction of the envelope form. The best remedy however, is to upgrade the locomotion model from instantaneous state changes to realistic maneuver dynamics. Currently, work is underway to improve the presentation of the vector envelopes, and perform a more elaborated evaluation. Future directions could be the extension to 3D navigation, i.e., including altitude; however, this poses some challenges regarding the visualization of the affordances. Further improvements could be inclusion of the turn and acceleration dynamics, as this would address the uncertainty about beam expansion, and it would also make the interface more generally applicable to other vehicles.

References

ACM Airborne conflict management: Application description v2.5 (2002), RTCA, Federal Aviation Authorities, Tech. Rep. RTCA SC-186.

Hoekstra (2001), J., *Designing for safety: the free flight air traffic management concept*, Ph.D. dissertation, Delft University of Technology. Amsterdam: NLR. ISBN 90-806343-2-8.

van Paassen, M.M., (1999), *Functions of space and travellers*, in XX European Annual Conference on Human Decision Making and Manual Control, Loughborough, United Kingdom.

De Neef, R., (2002), *Functional modeling of airspace: Definition and evaluation of a travel function for application to aircraft heading guidance*, Unpublished Msc. thesis, Faculty of Aerospace Engineering, Delft University of Technology.

Modarres, M., *Functional modeling applications association website*. http://www.enre.umd.edu/ifmaa/.

Gibson, J.J. (1979), *The Ecological Approach to Visual Perception*. Boston: Houghton-Mifflin.

Vicente, K.J. and Rasmussen, J. (1992). *Ecological Interface Design: Theoretical Foundations*. IEEE Transactions on Systems, Man and Cybernetics, Vol. 22, No. 4, pp. 589-606

Lind, M. (1990), *Representing goals and functions of flow modelling - an introduction to multilevel flow modelling.* Institute of Automatic Control Systems, University of Denmark, Tech. Rep. 90-D-381.